9 Tunable Free-Electron Lasers

Stephen Vincent Benson

Accelerator Division
Continuous Electron Beam Accelerator Facility
Newport News, Virginia

1. INTRODUCTION

1.1 Description of FEL Physics

The free-electron laser (FEL) uses a relativistic beam of electrons passing through an undulating magnetic field (a wiggler) to produce stimulated emission of electromagnetic radiation (Fig. 1). The quantum-mechanical description for this device is based on stimulated emission of Bremsstrahlung [1]. The initial and final states of the electron are continuum states so the emission wavelength is not fixed by a transition between bound states. Although the initial description by Madey was quantum mechanical, there was no dependence of the gain on Planck's constant. This is a necessary but not sufficient condition for the existence of a classical theory for the laser. In fact, it was found that the device was almost completely described by a classical theory [2].

The classical theory of FELs is an extension of the theory of the ubitron developed by Phillips [3,4]. The ubitron is a nonrelativistic version of the FEL. It was developed in a classified program between 1957 and 1964. It is a fast-wave variant of the traveling-wave tube (TWT) amplifier and uses a transverse motion of the electrons to couple a copropagating electromagnetic wave to the electron beam. The classical formulation is therefore similar to the formulation for a
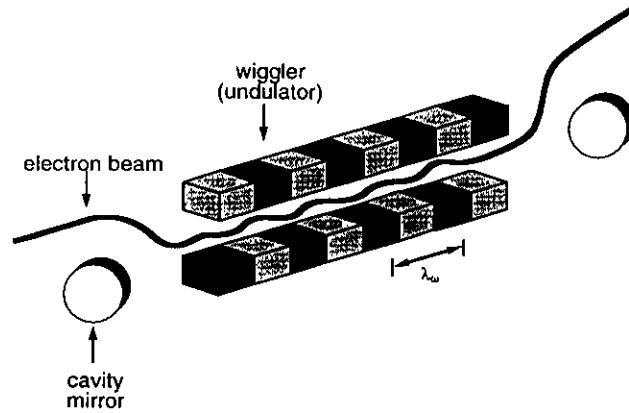
FIGURE 1   A schematic of a FEL oscillator is shown. The electron beam is bent into a wiggler using bending magnets (not shown). The electron beam wiggles along the optical axis of a cavity, which is collinear with the axis of the wiggler. The wiggler shown consists of alternating North (light gray) and South (dark gray) poles that alternately bend the beam left and right. The light is usually coupled out of one of the mirrors. In an actual device, the electron beam and usually the mirrors are in a vacuum chamber. The electron beam is shown as a continuous line, but in most devices it is a pulsed beam.

TWT amplifier. It describes the interaction as a bunching of the electrons at a wavelength near the resonant wavelength λ_0 defined by the relation

$$\lambda_0 = \frac{\lambda_w}{2h\beta^2\gamma^2}\left[1 + \left(\frac{eB\lambda_w}{2\pi mc^2}\right)^2\right], \tag{1}$$

where h is the harmonic number for harmonic lasing, B is the rms magnetic field in the wiggler, β is the speed of the electrons divided by the speed of light, γ is the electron-beam relativistic energy divided by its rest mass mc^2, and λ_w is the wiggler wavelength. Equation (1) assumes that the electromagnetic wave is traveling at the speed of light in a vacuum. Doria et al. have described the resonance condition for a FEL in a waveguide for which the phase velocity is greater than c [5]. We will assume here that the electromagnetic wave is traveling in a vacuum.

Figure 2 graphically shows how the resonance works. At the resonant wavelength, one wavelength of the optical wave slips past the electron in the time that the electron travels one wiggler period. At wavelengths near λ_0 the vector product E·v is slowly varying so that there is a net exchange of energy between the optical and electron beams. At exactly the resonant wavelength when the beam current is low there is as much electron acceleration as deceleration so there is no net gain. For wavelengths longer than λ_0 the interaction provides net gain for
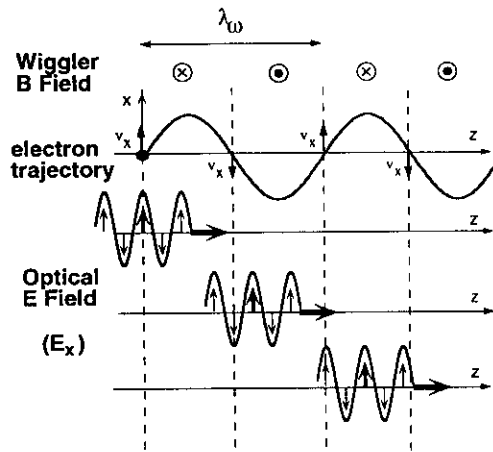
FIGURE 2   At resonance in a FEL the copropagating optical field slips past the electrons one optical period in the time it takes the electron to travel one wiggler period. The magnetic field is perpendicular to the page. The electron horizontal position oscillates as the electron travels down the wiggler. The optical field polarization is assumed to be horizontal. Note that, as the electron shown moves through the wiggler, it sees an electric field, which changes sign as it changes velocity. The electron therefore experiences a net deceleration as it goes through the wiggler. Other electrons may see acceleration or no effect depending on their initial phase with respect to the optical beam.

the optical wave and a net deceleration for the electrons, whereas for shorter wavelengths the interaction provides a net loss for the optical wave and net acceleration for the electrons. The functional form of the gain curve for a uniform wiggler is shown in Fig. 3. An interesting aspect about FELs is that gain and loss appear at different wavelengths so that, unlike conventional lasers, there is no threshold current for gain. The laser designer's task is therefore to provide gain that is sufficient to exceed resonator losses in the case of an oscillator or useful gain (usually an order of magnitude or larger) in the case of an amplifier.

The quantity in parentheses in Eq. (1), $eB\lambda_w/2\pi mc^2$, is referred to as the *wiggler parameter* (or sometimes the *deflection parameter*) and is typically represented by the symbol K. It is usually of order unity and can be calculated by the relation

$$K = 0.934 B(T)\lambda_w \left(cm\right) .\tag{2}$$

At low electron-beam energies, the space charge in the electron beam complicates the analysis because space charge waves can be set up in the electron beam that couple to the density modulation caused by the FEL interaction. When this occurs, the FEL is said to be operating in the Raman regime. When space charge waves are a negligible part of the interaction, the device is said to be
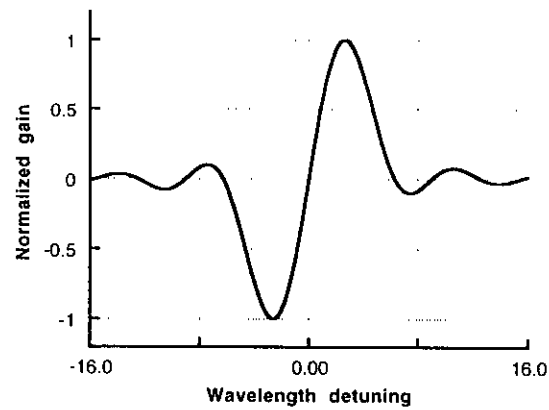
FIGURE 3 The normalized gain function versus the normalized wavelength detuning defined by $v = 2\pi hN_w\delta\lambda/\lambda$ is shown. The wavelength detuning is defined with respect to the resonant wavelength. At the resonant wavelength there is no gain. At longer wavelengths there is gain, and at shorter wavelengths there is loss. A uniform wiggler was assumed for this curve.

operating in the Compton regime. Because the space charge interaction varies in strength as γ^{-3}, lasers using highly relativistic electron beams are all Compton regime lasers. Note that the converse is not true; that is, a low-energy FEL is not necessarily a Raman device. In order for the gain to be enhanced by the space charge wave, the wiggler field must have a longitudinal component. This is not true in many low-energy Compton regime devices. Only Compton regime lasers are used in user facilities to date so I will confine my discussion to them.

Because the parameter γ is generally quite large compared to unity, the resonant wavelength can be much smaller than the wiggler wavelength. By varying the electron-beam energy, a single wiggler can support a very large range of wavelengths. As a result, FELs have operated in the Compton regime at wavelengths from 8 mm to 240 nm. An individual laser does not operate over such a large range, but FELs operating in three different wavelength ranges have demonstrated a tuning range greater than 8 to 1 in a single laser.

Other authors have given very complete descriptions of the theory of FELs. I will therefore not spend much space in this chapter on the details of free-electron theory. Interested readers are urged to consult Brau's excellent textbook [6] or Volume 4 of the *Laser Handbook* [7]. This chapter discusses the characteristics of FELs without going into much detail about how they arise and will study various means by which one may cover a broad wavelength range with a FEL. I then discuss some of the issues involved in achieving a large tuning range. FELs are large and expensive devices. They are therefore usually used in a user facility setting rather than an individual's lab. I will describe some of the broadly tunable lasers available at various user facilities around the world. Other free-electron

lasers exist that are not set up as user facilities but have many useful and interesting properties. These are not discussed here.

1.2 General Characteristics of FELSs

Although free-electron lasers have used many accelerator technologies, wiggler technologies, and optical resonator designs, they have several characteristics in common:

1. Because the electron beam is almost always smaller than the optical mode, the gain medium acts as a spatial filter and provides almost perfect mode quality. Efforts to disturb the optical mode by mis-steering or defocusing the electron beam reduce the power and gain with no apparent change in the optical mode structure. The laser beams out of the FEL can be focused to spot sizes limited only by the quality of the transport and focusing optics. There is no thermal distortion of the mode due to heating of the gain medium since the gain medium leaves the laser at the speed of light. The only refractive effects present in the gain medium have to do with the gain process and their only effect is to focus the beam slightly but not to change its beam quality. Because the saturated gain is independent of the small-signal gain (it is just a function of the total cavity losses), the output mode of the laser does not depend on the laser power.

2. FELs have high peak power. Electron-beam energies used to date range from a few megaelectron-volts up to 800 MeV. Peak currents are in the range of 2 to 500A. The peak electron-beam power in current experiments has therefore been between 4 MW and 36 GW. Power extraction is usually on the order of 1%, so the peak laser power is typically in the 0.1- to 10-MW range, though power in the gigawatt range has been demonstrated in lasers with better extraction efficiency. Although it has not been demonstrated to date, FELs are also capable of high average power. FELs to date have operated with up to 11 W of average power but the average laser power is limited only by the average power of the electron beam and the attainable efficiency (1% is typical but 45% has been demonstrated). Electron-beam powers as high as a megawatt have been demonstrated to date in electron accelerators, so kilowatt lasers are quite feasible.

3. FELs can have very short pulses. The bandwidth of a FEL can easily be as high as 10%. This leads to the possibility of very short optical pulses. Experiments have demonstrated subpicosecond pulses from FELs [8]. Note that no attempt to produce very short pulses was made in this case. Unlike many mode-locked lasers, the FEL has very little gain or power unless it has a very short pulse. When one optimizes the electron beam for maximum laser power, one automatically produces very short pulses. It has been suggested that chirping the energy of the electron pulses can produce chirped laser pulses that can be compressed in a prism pair [9]. Recently, researchers at Duke University have used this technique to produce optical pulses shorter than 250 fs in the 4-μm range.

4. FELs typically have low duty cycles. Because electron beams have such high peak powers, no continuous FEL has been demonstrated at this time. It should eventually be possible to construct a continuous FEL operating in the far-infrared region where an energy recovery electrostatic accelerator can be used, but a near-infrared or ultraviolet continuous wave (CW) laser would be exceedingly difficult to build. As noted, the electron-beam power required for lasing is many megawatts. Assuming even several percent efficiency, the exhaust beam from this laser would be a formidable problem. FELs therefore usually have a pulsed time structure, often with a micropulse/macropulse character as shown in Fig. 4. Compton regime lasers usually have very short pulses, ranging from 500 fs to 10 ps. The separation between these pulses ranges from a few hundred picoseconds to a few hundred nanoseconds. Researchers at CEBAF in Newport News, Virginia, are building a continuously pulsed FEL that will have 1-ps pulses separated by 40 ns. Just by eliminating the macropulse structure, the laser power in this design has been raised to the multikilowatt level despite a duty cycle of less than 10^{-4}. (The exhaust beam from this laser will be decelerated back down to low energy to reduce the problems of a megawatt beam dump and to increase the laser efficiency.) If one wants to increase the average power one usually does so by increasing the duty cycle, but even at the 100-kW power level the duty cycle will be less than 1%.

5. FELs are easy to tune. In fact, one design challenge in any FEL is to keep the wavelength under control so that it does not drift or jitter. When desired, tuning over a very large wavelength range is usually extremely easy. The optical cavity must be very broad band to take advantage of this tunability.

6. FELs exhibit harmonic lasing. This feature is described in more detail later. Lasing at a high harmonic can extend the operating range of a laser over a much larger wavelength range than is possible with only energy and field tuning.

7. FELs are large and expensive. This point has already been mentioned, but it alters the design of many lasers in ways that are not obvious. Efforts are under way around the world to make FELs more compact and inexpensive. The cost and size achieved to date however make it impractical for an individual investigator to purchase one. The best alternative is to use one at a user facility. The cost of using the laser at a user facility is not any more than using any smaller laser because many users do research at the FEL centers at the same time. The inconvenience of using a laser outside of one's own laboratory can be discouraging however. Most researchers who have the opportunity to use a conventional laser in their own laboratories to accomplish their research will do so if the wavelength and power are available. Due to this fact, most FEL centers do not plan for use of the laser where conventional sources are available (in the visible, near ultraviolet, and near infrared). Research requiring mid-infrared or deep-UV laser light at low average power can often use optical parametric generation or harmonic generation to produce light for their experiments. Researchers requiring light outside this wavelength range or requiring more average power (hun-
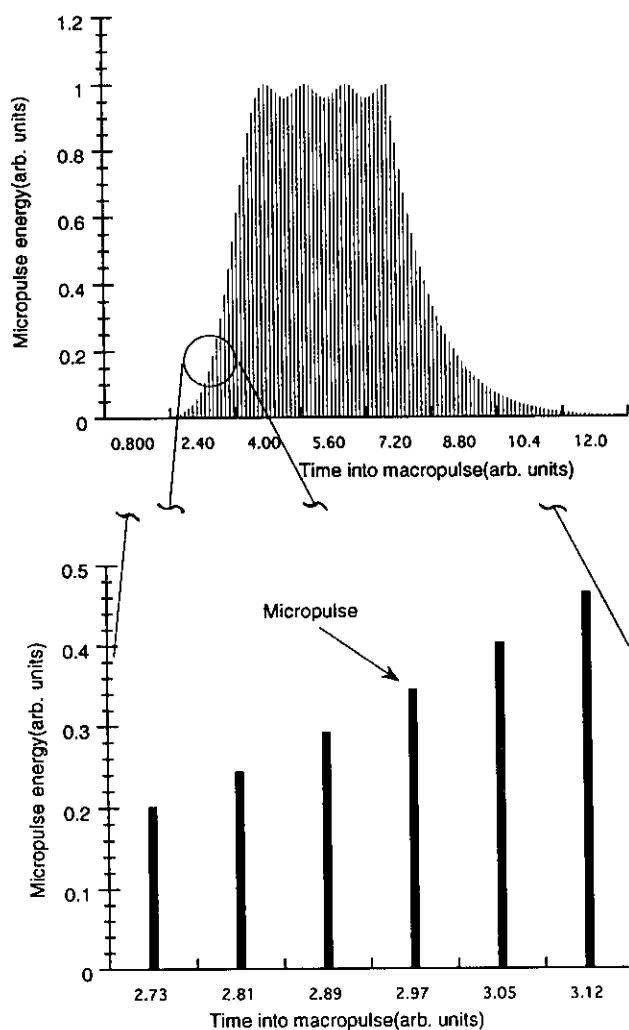
FIGURE 4   A typical time structure is shown for a laser pulse from a FEL based on a pulsed rf linear accelerator. The laser macropulse consists of hundreds of short micropulses. In most FELs operating to date, the micropulses are 1 to 10 ps in length and the macropulse is from 1 to 100 μs in length. The macropulses repeat at a repetition rate limited by the accelerator; usually in the range of several hertz up to 120 Hz. The micropulse repetition rate can be anywhere from several megahertz up to several gigahertz. The ripple on the pulse is due to modulations in the arrival time and energy of the electrons caused by effects in the microwave power source in the accelerator.

dreds of milliwatts or more) or a picosecond time structure may find that the FEL provides just the laser light source they need.

2. METHODS OF WAVELENGTH TUNING

Obviously one can vary the resonant wavelength defined in Eq. (1) by varying any of the four parameters on the right-hand side: the electron energy, the wiggler magnetic field, the harmonic number, or the wiggler wavelength. The last two of these are not continuously variable, so they are more useful for changing wavelength ranges rather than continuous wavelength tuning. There are good reasons for using these parameters to extend the wavelength tuning range, as will be shown later. I will discuss the advantages and disadvantages of each method of wavelength tuning. One should remember that the methods are not mutually exclusive but can all be used in one facility.

There are a few other means to tune the wavelength of the laser that I will not discuss in detail. One is changing the average angle of the beam. This method is usually not feasible because the gain degrades too strongly with the electron-beam angular spread. The second is gas-loaded operation [10]. This has been demonstrated on both the Mark III and SCAFEL lasers at Stanford University but is still very technically challenging to implement and has not yet achieved broadband tuning. Harmonic generation outside the laser has been demonstrated using conventional second harmonic generation techniques [11]. In principle, it is possible to drive an optical parametric oscillator or amplifier as well. These methods are quite useful when the wavelength range is limited by the design of the laser, but more power can usually be obtained by operating the laser at the desired wavelength.

2.1 Energy Tuning

The first demonstrated method of wavelength tuning was to change the electron-beam energy. This was done on the first FEL at Stanford [12] but the tuning range was limited to ±10% by the rather narrow reflectivity band of the resonator mirrors.

The group at Los Alamos National Laboratory (LANL) used copper mirrors with hole output coupling to change the laser wavelength from 9 to 35 μm by varying the electron-beam energy by a factor of approximately 2 [13]. The evidence for lasing at the longer wavelengths was indirect however (the output window was opaque to the laser radiation) so it was not known with certainty whether fundamental lasing was achieved over this range. In later work [14] the LANL team demonstrated lasing over a range of 9 to 45 μm with direct observation of the laser light.

The far-infrared laser at the University of California at Santa Barbara (UCSB) demonstrated operation at wavelengths covering the range of 200 to 800 μm [15]. Tuning via energy change was continuous only over a very small energy range due to the necessity of maintaining good energy recovery in the

electron beamline. This range has been extended to a 10% wavelength range (5% in energy) more recently by use of a computer control system [16].

The TRW/Stanford FEL collaboration was successful in achieving lasing between 4.0 and 0.5 μm by varying the electron-beam energy [17]. This laser uses the same superconducting accelerator used for the first Compton regime FEL.

Tuning the wavelength via energy change has several advantages and disadvantages. One major advantage is in the undulator design. A fixed undulator is simpler and less expensive to design and build than a tunable undulator. For an undulator with more than around 80 periods it becomes extremely difficult to built a wiggler whose field can be adjusted continuously. The wiggler parameter K can also be smaller. Most designs for compact wigglers result in values of K much less than unity [18–20]. These designs must therefore rely on energy tuning to achieve a broad tuning range.

Another advantage of energy tuning is that it can be exceedingly rapid. The laser should be able to tune at a rate of one gain bandwidth per turn-on time. This can lead to tuning across a range of 10% in tens of microseconds. The TRW/Stanford collaboration has demonstrated tuning of 2%/ms during a macropulse several milliseconds long. Researchers at LANL [21] and at the FELIX facility [22] have also demonstrated fast wavelength tuning via energy change. This feature might be quite useful in lidar applications.

The primary disadvantage to energy tuning is the need to readjust the entire electron-beam transport line leading to the laser. In some lasers this can be a very slow task. A good computer control system can, in principle, allow reasonably rapid scanning of the electron-beam energy over a factor of 2 range as is done in storage rings, but this has not been demonstrated in a FEL device to date.

The second disadvantage is that, if the beam current is fixed, the electron-beam power decreases as the electron energy decreases. Thus, the power out of the laser varies as the inverse square root of the wavelength. Because the gain often increases as the energy decreases, it is possible to change the undulator and increase the efficiency as the laser wavelength is increased. Just removing periods would present severe mechanical design challenges. It has been shown that introducing a taper to the wiggler field enhances the efficiency [23]. One can change the taper, and therefore the efficiency, as the wavelength is increased. In some accelerators, it is possible to reduce the energy by increasing the beam current while holding the beam power constant. This could also be used to tune the wavelength at constant laser power. A special case of energy tuning is that of a storage ring FEL, whose power is proportional to the third power of the electron-beam energy. The gain is not a steep function of electron-beam energy and tapering is not usually an option due to the energy aperture of the storage ring so energy tuning is not a good choice for storage-ring-based FELs.

Finally, in an energy recovery linac such as in the FEL planned for CEBAF, the efficiency for the overall system will decrease at lower electron-beam

energies. A taper in the undulator cannot be used to recover the power in this case since the deceleration leg has a limited energy aperture that would be exceeded for tapered operation.

2.2 Wiggler Tuning

The wiggler parameter can be varied by changing the magnetic field. If the wiggler parameter is approximately equal to or greater than unity, this can lead to large changes in the wavelength. In permanent magnet undulators one can vary the gap of the wiggler in order to vary the magnetic field strength. Electromagnetic wigglers can be varied by changing the energizing current. The group at Orsay pioneered gap tuning on the ACO storage-ring-based laser [24]. Continuous tuning was demonstrated over the bandwidth of the mirrors. The VEPP-3 project at Novosibirsk demonstrated continuous tunability over the range of several sets of mirrors by varying the current of their electromagnetic wiggler [25]. Both the Mark III FEL and the Rockwell FEL at Stanford used gap tuning to tune over a large wavelength range [23,26]. The Mark III could tune continuously over a 70% change in wavelength in a matter of seconds. This technique is also used at Vanderbilt [27], the CLIO project at Orsay [28] and the FELIX project at the FOM institute at Rinhuizen, The Netherlands [29]. The latter two systems have demonstrated two to one tuning range at a single electron-beam energy.

The advantages and disadvantages of this approach are opposite to those of the energy tuning approach. The power output is fairly independent of wavelength over a large range. Tuning the laser is quite simple. It is quite easy to design for single-knob tuning by a factor of 2 to 4. This can be quite convenient in a user facility, since no understanding of the computer control system is necessary for the user. The tuning control can even be isolated so that it does not interfere with the accelerator control system. The tuning cannot be carried out as quickly as energy tuning in a mechanically tuned wiggler but might be quite fast in a properly designed electromagnetic wiggler (especially a pulsed electromagnetic undulator).

The largest disadvantage is in the constraints placed on the wiggler construction. Wiggler tuning is only useful when one has a high K wiggler. Great care must be taken in the construction of the wiggler so that the input and output steering is independent of the magnetic field strength. The field quality of the wiggler must remain high as the wiggler is tuned. All these constraints are most easily satisfied for an electromagnet. There is more interest these days in using electromagnets in future user facilities. The proposed high-average-power facility at CEBAF uses an electromagnet to tune over a range of 4 to 1 [30]. A new facility at Princeton University will use a superconducting wiggler in a compact infrared FEL (CIRFEL) [31] built by Northrop–Grumman.

2.3 Harmonic Operation

Operation of a FEL at an odd harmonic of the fundamental wavelength was first proposed by Madey and Taber [32]. The full theory of harmonic lasing was given by Colson in 1981 [33]. The gain at the harmonic can actually be higher than that of the fundamental. If one is using this approach to lase at a short wavelength without raising the energy of the accelerator, the wiggler parameter K must be greater than unity for the harmonic gain to be higher than the gain at the fundamental. The gain at the harmonic is much more sensitive to degradation by the energy spread and emittance of the electron beam, as well as the wiggler field quality, so in practice the harmonic gain is rarely higher than the gain at the fundamental for most existing systems.

Experimental verification of third harmonic lasing was demonstrated in 1987 at Stanford [34], in 1988 at LANL [35], and in 1992 at Orsay [28]. Lasing at harmonics higher than the third has not yet been demonstrated. Warren has proposed that operation at very high harmonics may be a good way to operate a compact FEL [36]. The analysis below is a summary of his approach. An approximate gain formula for a FEL with a linearly polarized wiggler takes the form

$$g = 0.004 I \gamma Q N_\beta^2 \eta_\epsilon \eta_\gamma \eta_f \eta_\mu \ , \tag{3}$$

where I is the peak current, $N_\beta = N_w K / \gamma$ is the number of betatron periods in the wiggler, Q is a factor that depends on the wiggler parameter and the harmonic number h:

$$Q = \frac{h^2}{1 + K^2} \left| J_{(h-1)/2}(h\xi) - J_{(h-1)/2}(h\xi) \right|^2 \ , \tag{4}$$

where the variable ξ is given by

$$\xi = \frac{K^2}{2(1 + K^2)} \ , \tag{5}$$

η_γ is the gain degradation due to the energy spread,

$$\eta_\gamma = \left[1 + \left(4\sqrt{2}\, hN\sigma_\gamma / \gamma \right)^2 \right]^{-1} \ , \tag{6}$$

η_ϵ is the gain degradation due to the rms emittance ϵ (the emittance is a measure of the transverse phase space area occupied by the electron beam distribution)

$$\eta_\epsilon = \left| 1 + \eta_\gamma \left(4\pi^2 \epsilon N_\beta / \lambda \right)^2 \right|^{-1/2} , \tag{7}$$

η_f is the filling factor for the optical mode

$$\eta_f = \left(1 + 4\pi \epsilon / \lambda \right)^{-1} , \tag{8}$$

and η_μ is the gain degradation due to slippage effects

$$\eta_\mu = \left| 1 + \left(hN\lambda / 3\sigma_z \right) \right|^{-1} , \tag{9}$$

where σ_z is the rms electron pulse length. The gain degradation due to the energy spread and the emittance are similar to inhomogeneous broadening effects in conventional lasers and arise because some of the electrons have a resonant wavelength that differs from the resonant wavelength of an average electron by a large fraction of the gain bandwidth. The gain reduction due to the filling factor is simply the result of an overlap integral between the optical mode and the electron beam. Equation (8) assumes that the optical mode and the electron beam are focused optimally in the gain region. Because the gain medium can affect the actual optical mode waist, this equation is an approximation. Three-dimensional simulation codes can be used to get a better estimate of this term. The gain reduction due to slippage occurs when the Fourier transform of the electron bunch shape in time has a spectral bandwidth comparable to or larger than the gain bandwidth. This reduces the coupling of the electron beam to the optical pulse.

Given the electron-beam parameters such as emittance ϵ, energy spread σ_γ, the peak current I, and energy γ, it is possible to design an undulator that produces a gain reduction parameter η_ϵ or η_γ of 0.5. Warren showed that for large values of ϵ/λ the harmonic at which both gain degradation factors were equal to 0.5 can be quite high. Unfortunately, the gain is usually too small to be useful when this is the case. For small values of ϵ/λ it is still possible to design the wiggler that sets η_γ equal to 0.5, and one finds that the values of η_ϵ and η_f are always greater than 0.5. If one wants to work at a high harmonic, the number of wiggler periods is usually quite small. Because the gain reduction due to slippage is the same for all harmonics, the value of η_μ is usually close to unity.

The value of Q for a given harmonic number and optimum K varies very little. This is shown in Table 1, which lists the optimum value for Q and the K for which the maximum value occurs. Also listed are the values of K for which the value of Q falls by 10% and 50% from its peak value. As can be seen from Table 1, the optimum value for Q varies little from $h = 3$ to $h = 15$. This implies that,

if the inhomogeneous gain reduction factor, slippage factor, and filling factor do not degrade very fast with harmonic number, the gain will be fairly independent of harmonic. In addition, the values for $K_{90\%}$ are in the accessible range of 1 to 2. Warren *et al.* have pointed out that wiggler parameters around unity can be achieved for periods as short as 3 mm by using a pulsed electromagnetic wiggler [37]. Efforts to operate a FEL using such a wiggler have thus far failed [38].

As an example of a system that can achieve broadband tunability by harmonic lasing, I have calculated the gain versus wavelength for a laser operated in the infrared using an electron beam with parameters similar to those present in the LANL APEX photoelectron injector operated at 20 MeV [39] or the Princeton CIRFEL device [31]. Such a device would be quite compact and would be capable of lasing between 3 and 80 μm with gains in excess of 30%. At each harmonic the wavelength would be varied by tuning the electron-beam energy.

2.4 Wiggler Wavelength Tuning

No one has come up with a method by which the wiggler wavelength can be continuously tuned. The wavelength of any wiggler is essentially fixed. Nevertheless, one can choose wavelength bands by selection of the wiggler wavelength. A large part of the cost of a FEL is the electron source. Once this is available, one can produce several undulators and optical cavities, each of which covers a wavelength band for which it is optimized.

This concept is so appealing that several user facilities are adopting it. The FEL facility at UCSB is in the process of installing a set of three FELs on its accelerator which will cover these ranges: from 2 mm to 300 μm, from 300 to 63 μm, and, using third harmonic lasing, from 63 to 30 μm. The design tuning range is therefore extended from the 8 to 1 range available in an individual laser to 67 to

TABLE 1   Maximum Values for Q at Several Harmonic Numbers and the Wiggler Parameters for Which the Maximum, 90% of Maximum, and Half of Maximum Occur

h	Q_{max}	K_{max}	$K_{90\%}$	$K_{50\%}$
3	0.36064	1.064	0.832	0.566
5	0.30946	1.428	1.158	0.852
7	0.28843	1.684	1.383	1.048
9	0.27665	1.886	1.560	1.200
11	0.26901	2.057	1.709	1.327
15	0.259521	2.337	1.953	1.533

1 for the entire system. See Sec. 5.6 for a more complete description of this facility. The FELIX FEL (Sec. 5.3) user facility in the Netherlands also uses two undulators to cover the wavelength range of 6 to 110 μm, thus covering a wavelength range of 18 to 1. Finally the Stanford Picosecond FEL center (see Sec. 5.5) has three wigglers available covering a 21 to 1 wavelength range from 3 to 64 μm.

3. BROADLY TUNABLE OPTICAL CAVITIES

A broadly tunable FEL offers some unique design challenges for the optical cavity designer. Difficulties arise from three features of the laser—the need for broad tunability, the extremely high saturation intensity of the device, and the fact that the gain medium is almost always smaller than the optical mode.

3.1 Mirror Technologies

It is obvious that broadly tunable lasers in the infrared to millimeter range should be able to use metal mirrors to achieve high damage thresholds, broad tunability, and reasonable optical figure. Metal mirrors can withstand pulsed fluences in the infrared as large as 50 J/cm^2 for a microsecond. The damage threshold scales as the square root of the pulse length (e.g., the damage threshold is 5 J/cm^2 for a 10-ns pulse). For some lasers with long macropulses and a low micropulse repetition rate, the damage threshold must be calculated for both the macropulse fluence and the micropulse fluence. The smaller of the two should then be used. For very long macropulses the power density is limited by thermal distortion. Commercially available mirrors can easily tolerate 1 kW/cm^2. The metal can be deposited on a low expansion coefficient material such as SiC for cw operation in order to improve the figure. Pulsed operation generally requires a good match between the metal coating and the substrate to keep the coating from flaking off the substrate. Silver on copper has proven to be a good combination.

At shorter wavelengths, dielectric mirrors must be used. This limits the damage threshold and tunability. Removal of heat deposited in the mirrors also poses design challenges. There is usually a trade-off of damage threshold and bandwidth in dielectric mirrors, so the range of tunability of the mirrors is usually only around ±10%. At least a dozen sets of mirrors might be needed to cover the range of 1.5 to 0.2 μm. Fortunately, the fact that a mirror can be used at odd harmonics of the design wavelength can reduce the number somewhat. It is also possible, in lasers with low power loading in the mirrors, to use broadband coatings similar to those used in some dye lasers or Ti:sapphire lasers. These coatings can extend the wavelength tuning range to ±25%. Dielectric mirrors may also be used as output couplers in low-gain infrared lasers operating between 1 and 15 μm. At longer wavelengths, it is difficult to find a transparent substrate. Changing mirrors can be accomplished easily if the mirrors are not in the vacuum chamber. If they are

inside the vacuum chamber, the mirror change can take anywhere from a couple of hours to a couple of days depending on the quality of vacuum desired. Many user facilities are considering the use of *in vacuo* turntables so that the vacuum does not have to be broken to change a mirror.

3.2 Unstable Resonators

If one has an optical cavity with all metal optics the obvious question arises of how to couple the laser power out of the cavity. One common method to accomplish this is to use an unstable resonator [40]. Because the gain medium is unidirectional, an obvious design is the negative branch ring unstable resonator [41]. No FEL has been operated in an unstable mode in order to outcouple the laser light. A couple of lasers have been operated in an unstable configuration either by accident or with dielectric mirror output coupling [42,43]. Due to the small gain volume of FELs and their relatively small saturation gain, the only possible unstable resonator designs are negative branch nearly confocal cavities. This allows the mode to be quite small in the gain region while keeping the mode large on the output coupler. One can have a cylindrically symmetric cavity or have one axis of the cavity stable and one unstable as proposed by Siegman [44]. The stable/unstable cavity has the advantage of a slower change in the optical mode size as the wavelength is changed. Shih has studied how to configure the stable/unstable cavity in order to optimize the output mode quality [45].

3.3 Brewster Plate Output Coupling

Because the light from a FEL is usually strongly linearly polarized one can install a Brewster plate in the cavity without adding to the cavity losses (with the exception of scatter and absorption, which can be kept quite small). If one then rotates the plate by a few degrees, one can increase the losses by a calculated amount. The light can then be deflected out of the laser mode and through an output window. There will be four reflections from the plate, two in each direction. Because the Brewster angle is insensitive to wavelength, the cavity is quite broadband. The optical mode quality is quite good for each of the four reflections. One also has the interesting possibility of continuously variable output coupling. There are, however, many disadvantages of this method.

1. If one uses a parallel plate, one gets two almost overlapping spots in the output beam separated in time. This is bad for any applications that require individual pulses or diffraction-limited spots. If one wedges the plate, one can eliminate the extra spot with the penalty of decreased output coupling efficiency. One can use a separate mirror to recover at least one of the two backwards reflections, but this also reduces the mode quality.

2. The choice of materials is quite limited. The Brewster plate material must be a very high quality material with exceedingly high transparency over as large a wavelength range as possible, very high damage threshold, high radiation damage threshold, and good optical figure. In the visible and near infrared, fused quartz or silica are good choices. Sapphire can also be used but must be carefully oriented to preserve the polarization of the beam. In the infrared, zinc selenide and barium fluoride are the best choices. Barium fluoride has a higher damage threshold but smaller transparency range and lower radiation damage threshold. Zinc selenide is a semiconductor and is subject to a relatively low damage threshold and multiphoton absorption leading to nonlinear losses, though it is remarkably free of radiation damage due to its large band gap. Between approximately 15 and 100 μm there are no good materials available for use, though CVD diamond films show promise as pellicle Brewster plates. Salts are transparent in most of this range but are exceedingly sensitive to radiation.

3. The plate adds dispersion to the cavity and forces one to change the cavity length as the wavelength changes. This is not always a disadvantage. Brewster plate dispersion was used to separate the fundamental and harmonic lasing in the first third harmonic lasing experiments [34]. The cavity length change is well defined and can be programmed into a computer control system to change the cavity length as the wavelength is changed.

3.4 Hole Output Coupling

Several FELS have used a hole in the mirror to couple the power out of the laser. This was tried in conventional lasers but was found to be inefficient due to the tendency of the optical mode to avoid the hole [46,47]. In a FEL the gain medium interacts much more strongly with the lowest order Gaussian mode than with the higher order modes so that the mode with the highest net gain is not the same as the mode that has the lowest loss [48]. This leads to reasonably efficient output coupling via a hole in one end mirror. The scatter and diffraction off the hole edge limits the output coupling efficiency (defined here as the power transmitted through the hole over the total cavity losses) to no more than 50% for small output coupling. One potential problem is the change in the output coupling as the wavelength, and therefore the mode size, changes. Xie and Kim [48] have demonstrated using Fox and Li simulations that broad tunability can be achieved in a hole coupled resonator while keeping the output coupling efficiency higher than 40%. Hole output coupling has the additional advantage of allowing one to image the hole onto one's experiment and obtain a spot size that is independent of the wavelength. Typically, the damage threshold of the mirror is greatly reduced by the presence of a sharp edge near the center of the mirror. At this point hole output coupling has proved to be the best compromise among the available cavity designs for lasers in the mid-infrared to the far-infrared regions. It is not without disadvantages but it has the least problems of all available designs.

3.5 Focusing Effects

The optical cavity has a stronger effect on the gain of a FEL than in most conventional lasers and the gain can also affect the optical mode. The gain is maximized for an optimal overlap between the electron beam and the optical mode. As noted in Sec. 1.2 the electron beam acts as a spatial filter and typically produces a diffraction-limited beam in the absence of cavity figure errors. Note that the gain medium does focus the optical mode and therefore can change the waist size and location of the optical mode in the cavity from the cold cavity case (though the mode remains diffraction limited). This can be a problem in a system with an inflexible optical transport line. Some matching capability may be necessary to take advantage of the change in mode characteristics with the saturated laser gain (which is a function of the output coupling).

4. WIGGLER CONSIDERATIONS

Since wigglers are used on both FELS and storage ring synchrotron radiation sources, they have an extensive development history. The state of the art at this writing can produce wigglers with periods of a few millimeters up to tens of centimeters with fields of up to a tesla and precision approaching the measurement accuracy. Each type of wiggler is optimal for a given wavelength range. I will describe them in decreasing order of wavelength. A common denominator of widely tunable wigglers is the need for a gap that is sufficiently large for the longest optical wave to propagate with low losses. This implies that the wiggler will need a large field at a large gap. The vacuum chamber is usually inside the gap and reduces the available aperture for the optical mode. Typical period to gap ratios are as small as 2 to 1. Because the maximum field varies inversely as the exponent of this ratio, it makes little sense to make the ratio much smaller.

4.1 Room-Temperature Electromagnets

Devices with a large bore and a long wavelength benefit from the use of an electromagnetic wiggler. This design has the disadvantage of requiring a large power supply and cooling for the wiggler and cannot have a wiggler period shorter than around 5 cm due to the nature of the power density scaling [49], but it has several very advantageous features for a broadly tunable laser. The wiggler is rather inexpensive to build. It is usually less than one-half the cost per meter of any other design even when the cost of the power supply is included. The tuning is rapid and easy to interface to a computer control system. Because the field integral is usually independent of the excitation, the trajectory is usually nearly ideal at all field strengths. The laser behavior is therefore nearly optimized at all wavelengths if it is optimized for one wavelength. Shaw [50] has demonstrated

rapid single-knob tuning in the far infrared using an electromagnet, and the VEPP-3 laser at Novosibirsk has turned over the transparency range of several sets of mirrors with their electromagnetic optical klystron [25].

4.2 Permanent Magnets

One can also use arrays of permanent magnets, either by themselves or using flux concentrating iron poles, to make a high field wiggler. In applications where the ionizing radiation levels can be kept reasonably low, the material of choice is neodymium iron boron due to its high remanent field. When the radiation levels might be too high ($>10^7$ rad/year absorbed dose in the wiggler), the best material is samarium cobalt. A permanent magnet wiggler has the advantage of needing no power supply, except when the field is being changed. It also can be scaled down to wiggler wavelengths as short as 1 cm or less. The maximum field is dependent only on the type of material used and the gap to period ratio. Permanent magnet wigglers are relatively expensive to build. They become even more expensive if the field strength must be varied because they must be trimmed to keep a good field at many different gaps. The forces pulling the jaws together can be several tons so the mechanism used to support the jaws must be carefully designed. Fixed gap wigglers can be much simpler to build and tune. The group at UCSB has developed a robot adjuster that adjusts the pole positions in response to measurements of the field strength for each pole [16]. This had resulted in some extremely high-quality wigglers. Most user facilities use gap tunable permanent magnet wigglers at this point.

4.3 Superferric Magnets

Researchers at Brookhaven National Laboratory (BNL) have been developing a type of electromagnet wiggler that can be scaled down to wavelengths much shorter than 5 cm. By using superconducting wire they are able to have much higher current density and reduce the wiggler period to as little as 8 mm while maintaining fields close to 1 T (rms $K>0.5$). This design has not yet been used for an FEL but it is planned for use in a FEL at BNL and eventually at Princeton University. It has all the advantages of the normal conducting electromagnets plus the ability to get to a shorter wavelength. It has the disadvantages, however, of the cost and inconvenience of cryogenics. If one is using a superconducting accelerator this is not as much of a problem since the cryogenic support services are on site.

5. TUNABLE LASER FACILITIES AND THEIR CHARACTERISTICS

Many user facilities in the United States and Europe are now providing beam time to users. Most of them have made a large effort to provide as large a

range of wavelength coverage as possible. This section describes the major facilities available now and one facility that is scheduled to come on line shortly. More detailed information can be obtained from the individual institutions. Interested readers can contact the institution which seems to have the best match of capabilities and submit a proposal to use their facility. Each facility has strengths and weaknesses and is best matched to a given range of experiments. For each laboratory, I will describe the available wavelength range, the power available over the wavelength range, the temporal and spectral structure, and any unique features of the facility. Most of the facilities are driven by rf linacs and therefore have a micropulse/macropulse structure, so the power quoted in the literature may be peak power during the micropulse, average power during the macropulse, or, rarely, the long-term average power. One can also quote micropulse energy or macropulse energy. For most research applications average power is unimportant. The energy per macropulse and micropulse and the pulse lengths are usually the most important quantities. For all the facilities, the mode quality is nearly diffraction limited, so that feature will not be discussed here. Another common feature is that the lasers are generally locked to the a-c line frequency for stability purposes. Some of the properties of the facilities are listed in Table 2. Note that only ranges of power and pulse lengths can be given since they often vary by as much as a factor of 10 as the wavelength is changed. The power, microbunch length, and spectral bandwidth in rf linear accelerator-based devices can be strongly dependent on the cavity length, sometimes varying by as much as a factor of 10. It is therefore useful for the user to have control of the cavity length to optimize the power, bunch length, or spectral width. Note that

TABLE 2   Properties of User Facilities around the World[a]

Location of facility	Wavelength range (μm)	Micropulse frequency (MHz)	Macropulse frequency (Hz)	Micropulse power (MW)	Macropulse power (kW)
CLIO, Orsay, France	2–17.5	31–250	1–50	1–10	1–6
Mark III, Duke University	2–9	2857	1–30	0.5–3	2–30
FELIX, FOM, Netherlands	6–100	1000	5	0.1–3	1–10
CIRFEL, Princeton University[b]	5–15	142.8	10	1–5	1–7
SCAFEL, Stanford University	3–64	11.82	1–120	0.1–1	0.001–0.01
CFELS, UCSB	62–2500	[c]	0.25–4	[c]	1–27
Vanderbilt University	2–7.7	2857	1–30	1–10	2–30

[a]For more details, see the text descriptions. Third harmonic lasing is not included in the wavelength range when available.
[b]System being commissioned.
[c]This accelerator has no micropulse structure.

the pulses are usually transform limited so that the product of the spectral band-width and the pulse width is approximately constant.

There are several new user facilities either proposed or under construction in the world. I have included one of them to show that the trend is toward smaller devices with larger energy per micropulse and a lower energy electron beam.

5.1 CLIO, LURE

The *Collaboration pour un laser infra-rouge* or CLIO project has con-structed a user facility using a FEL at the Laboratoire pour l'Utilisation de Radi-ation Electromagnetique (LURE) at la Université de Paris Sud in Orsay, France. It has been in operation since mid-1992 [28]. This laser has operated in the range of 2 to 17.5 µm using Brewster plate output coupling with a ZnSe Brewster plate and using hole coupling. The power is rather insensitive to wavelength over the range of 3 to 12 µm with peak powers in the range of 1 to 10 MW as measured at the experimental table. The power drops at the long-wavelength end of the range due to diffraction. In fact, the laser is lasing quite nicely at 17.5 µm but the output beam is poorly matched to the transport line [51]. The power drops rapidly at short wavelengths due to reduced gain. The wavelength can be tuned over a range of a factor of 2 at any given electron-beam energy using gap tuning of the permanent magnet wiggler. Different wavelength ranges can be reached by running the accelerator in one of four energy settings. The wavelength can be changed by wiggler tuning in seconds. The electron-beam energy can be changed in approximately 20 min. Although they have succeeded in operating the laser at 3.3 µm using third harmonic lasing, the power was lower than when the laser was operated at the fundamental at the same wavelength.

The wavelength spread is typically about 0.4% full width at half-maximum (FWHM) over most of the wavelength range, though it can vary from 0.2 to 3% depending on the wavelength and the cavity length. The center wavelength is stable to approximately 0.2% over a period of hours. The user has control over the cavity length in order to optimize the laser for his or her needs. The user can also scan the wavelength with a resolution of 0.2% (one usually quotes resolu-tion in cm^{-1} but the resolution of this device is really a function of the wave-length so it is 1.1 cm^{-1} at 17.5 µm and 8 cm^{-1} at 2.5 µm).

A unique feature of this laser is the possibility of a variable micropulse time structure. The macropulses are up to 10 µs long at a repetition rate up to 50 Hz. The micropulse repetition rate can be varied from 31.25 MHz (32-ns separation) up to 250 MHz in steps of a factor of 2. In operation to date they have operated at up to 125 MHz. The micropulses are quite powerful with energies up to 40 µJ. With a micropulse time separation of up to 32 ns it is possible to carry out exper-iments that require only a single pulse hitting the sample or those requiring a sample to relax before the next pulse. The micropulses are typically 1 to 6 ps in

length. Recently they have succeeded in operating in a mode with very short pulses of only 500 fs [52].

There are four user rooms serviced by the purged optical beamlines. The users are supplied with basic optical equipment such as optical benches, detectors, and monochromators, and, because LURE is a synchrotron light user facility, there are many user services such as machine shops and electronics shops.

As with most facilities there is always interest in extending the wavelength range and improving the performance in other ways. There is only one laser on the accelerator and they have no room to add another. They therefore must modify the laser they have to improve the performance. One simple upgrade is to increase the repetition rate of the electron beam in order to increase the average power. They expect to be able to operate with up to 10 W of output power in the mid-infrared region. The second upgrade, already complete, is to replace the wiggler chamber bore to reduce diffraction and allow operation at longer wavelengths.

5.2 Duke University

Duke University runs a small user facility using an infrared FEL similar to the one used at Vanderbilt University (see Sec. 5.7). The so-called Mark III IRFEL [26] operates in the range of 2 to 9 μm on the fundamental and has operated at the third harmonic at wavelengths between 1.4 and 1.7 μm. As in the CLIO device, the long-wavelength end is determined by the diffraction in the wiggler bore, and power drops rapidly at wavelengths longer than 8 μm. The maximum power is available between 3 and 5 μm. The peak power is approximately 1 to 3 MW delivered to the optical bench. The average power during the macropulse varies from 2 to 30 kW depending on the wavelength and the output coupler used. The wavelength can be tuned over a factor of 1.7 by gap tuning the wiggler. Changing the energy can take several hours so user time is scheduled to make use of similar wavelengths on any given day.

The output coupling is via a Brewster plate output coupler. They have recently tried out hole coupling with mixed results [53]. The time structure has micropulses arriving at 2.857 GHz and 1- to 4-μs macropulses occurring at a repetition rate of up to 30 Hz. The spectral bandwidth is typically 0.5% FWHM in the 2- to 4-μm wavelength range, increasing to approximately 1% at the long-wavelength end of the range.

The user area is quite small with one user table available, and the user time available for outside use is less than at other infrared facilities in the United States but the lab has an active machine physics program, which results in a machine with great flexibility. Researchers at Duke have phase locked the microbunches in the laser, thus increasing the mode spacing in the frequency domain to 2.857 GHz [54]. One of the modes was then filtered out and high-resolution spectroscopy was carried out with it. The lab is also working on pulse

compression to achieve subpicosecond pulses tunable over the 2- to 4-µm range [9]. The beam is transported to the user room in a dry-air purged transport line. Various other lasers and a wet lab for biological or chemical preparations are available to users. Users have control over the wiggler gap, the cavity length, and the mirror steering. The macropulse length and the output coupler can easily be changed by the operator on request.

The lab is in the process of commissioning a storage ring-based FEL operating in the UV to VUV. This laser will be phase locked to the infrared laser but with a lower repetition rate of only 2.79 MHz. The present plan is to modify the accelerator for the infrared laser so that the repetition rate will be lowered to only 89.28 MHz. This modification would also allow greater micropulse energy and the ability to do pump probe experiments with a relatively long relaxation time. With the UV laser running, the facility will be capable of doing two-frequency pump probe experiments with one wavelength in the UV and one in the infrared. This upgraded facility may be available sometime in 1996. The lab has also proposed adding an addition to the lab that will provide approximately 13,000 ft^2 of additional lab space to the facility.

5.3 Institute for Plasma Physics, FOM

This well-run facility at the FOM Institute in Rinhuizen, the Netherlands, offers users a very large range of wavelengths in the infrared. The facility has two lasers, which, between them, cover the wavelength range between 6 and 100 µm. The first laser, called FEL-1, has a design wavelength range of 17 to 80 µm and has been operated betweeen 16 and 110 µm with usable power over the range of 16 to 100 µm. The average power during a 10-µs macropulse is greater than 1 kW (or micropulse energy of 1 µJ) over almost all of this range. The power versus wavelength curve has a broad peak of 10 kW between 25 and 50 µm. The second laser, FEL-2, has a design wavelength range of 8 to 30 µm and has been operated in the range of 6 to 20 µm to date. The power levels are again in the kilowatt range or larger over most of the available wavelength range. The first laser can tune over a wavelength range of a factor of 2 at a given energy. The second laser can tune over a factor of 3 due to its smaller vacuum chamber.

Because the mircopulse repetition rate is high (1 GHz) it makes sense to phase lock the micropulses as is done at Duke (in fact, they tend to phase lock without any effort due to the good coherence of the electron beam). Once the modes are locked, a single mode can be isolated from the frequency comb of the spectrum. Due to the long wavelength and short electron bunches, it is quite easy to trade off the spectral bandwidth and microbunch length [29].

There are six rooms available to users with all necessary utilities and signals provided. The optical beam is transported to the user area via an evacuated

beamline. The user facility is now an international user facility and will provide increased user time and more facilities for the users.

5.4 Princeton/Northrop–Grumman [31]

This compact facility, being constructed by Northrop–Grumman at Princeton University, is designed to provide operation in the wavelength range of 5 to 15 μm with high-energy micropulses produced at 142.8 MHz. Initial operation should be in the long-wavelength end of the design range since they are using a permanent magnet wiggler from LANL. Later operation will use an 8-mm period superferric undulator developed in collaboration with BNL. This will allow operation down to the shortest wavelengths in the range. The facility will be a university-based user facility rather than a national user facility.

5.5 Stanford University [55]

This user facility uses a superconducting accelerator to provide lasing in the infrared from 3 to 15 μm with very long macropulses of several milliseconds and a large separation between micropulses of 84.6 ns. The macropulses can occur at up to 120 Hz. The long separation between micropulses allows for samples to cool or relax between pulses and also allows the use of acousto-optic or electro-optic switches to pick out single pulses with good contrast. The microbunches have typically about 0.1 to 1 μJ of energy so the power in the laser beam delivered to the lab is on the order of 1 to 10 W during the macropulse. The micropulse length can be varied from one to several picoseconds in length so the peak power is from 0.1 to 1 MW during the micropulses. The facility has three operational lasers, with one operating in the near infrared from 3 to 8 μm, the second operating in the mid-infrared region from 5 to 15 μm, and the third operating in the far-infrared region from 18 to 64 μm.

The spectral bandwidths range from 0.1 to 1% FWHM. Due to a rather low gain, the laser must usually operate with dielectric optics so the user is generally limited to the wavelength range of the set of mirrors for the length of a shift. The mirrors can be changed in a couple of hours to change the wavelength range. The wavelength is changed by changing the electron beam energy.

The unique features of the Stanford facility include the following:

1. The wavelength is extremely stable. Using feedback techniques, it is possible to hold the wavelength stable to 0.01% over hours. The user can vary the wavelength over several percent using a single knob.
2. The wavelength can be slewed by several percent during the macropulse in any pattern the user desires. This may be useful in some vibrational studies.

3. The facility has tunable dye and Ti:sapphire lasers that are phase locked to the FEL so that two-frequency pump probe experiments can be carried out. The rms timing jitter between the two lasers is less than 5 ps.

There are eight experimental areas available for the users. Extensive diagnostics, an FTIR, and other non-mode-locked lasers are also available to users. This facility is quite well suited to chemical studies due to its good wavelength stability and slow micropulse repetition rate.

In the future the lab plans to upgrade the facility to include the use of a long-wavelength laser operating at wavelengths out to 100 μm. The laser has already been operated and is being commissioned. There are also plans to upgrade the electron-beam current to provide more energy per micropulse as well as more average power. In principle, one of the lasers at Stanford could provide hundreds of watts of average power in a mode-locked diffraction-limited beam.

5.6 University of California at Santa Barbara [16]

This facility is quite unique in that it uses an electrostatic accelerator instead of an rf linac to accelerate the beam. This results in quite a different temporal structure. There are no micropulses. The laser operates with pulses lasting up to 20 μs at a repetition rate of up to 4 Hz. The facility has two lasers operating, which provide wavelength coverage from 2.5 mm to 340 μm for the long-wavelength laser and 313 μm to 62 μm for the short-wavelength laser. The short-wavelength laser typically operates between 2 and 6.5 kW of output power. This can be enhanced somewhat by using a cavity dumper to produce tens of kilowatts of power for approximately 30 ns. The long-wavelength laser tends to operate for shorter macropulses but higher output powers with powers up to 27 kW available.

The laser usually operates with several longitudinal modes present in the cavity. With some care it is possible to injection lock the laser to an external laser, producing single-longitudinal-mode operation. The wavelength is tuned via changes in the electron-beam energy. This may be accomplished by computer tuning of the accelerator and electron-beam optics over a range of up to 10% in wavelength. Setting up a new wavelength may take anywhere from a few minutes to a few hours depending on whether the laser has operated at that wavelength in the past.

The laser output coupling is via hole coupling. The light is transported through an evacuated beamline to the four user areas.

The laser facility is used primarily to study heterostructures and other electronic materials although it is possible to use it to do any useful research in that wavelength range. Condenses matter interactions are the most obvious applications but some interesting biophysics experiments are also being carried out there.

There are plans to extend the wavelength range to shorter wavelengths by using a third wiggler operating at the third harmonic. This would provide light in the 30- to 90-μm range with kilowatts of power during the pulses.

5.7 Vanderbilt University [56]

This laser is very similar to the Mark III laser at Duke. In fact, the design of the Mark III was used to build the laser at Vanderbilt. The user demand at Vanderbilt has resulted in a slightly smaller tuning range of 7.7 to 2 μm, though the laser should be capable of going to longer wavelengths. The macropulses are approximately 5 μs in length and the energy per macropulse can be as high as 350 mJ. All these results were obtained using a Brewster plate output coupler. The laser has recently been modified to allow output coupling via a dielectric mirror. The peak power was improved greatly at the expense of some average power. The micropulse energy is as high as 10 μJ with macropulse energies as high as 200 mJ. The mirrors are mounted in a purged chamber so that mirrors can be changed in minutes.

The wavelength can be tuned via gap tuning over a range of $\pm$25% by the user. Larger changes take less than an hour. A typical laser linewidth is 0.7% though it can be smaller at the smaller wavelengths and larger at the longer wavelengths. The wavelength is continuously monitored in the control room using a low power pickoff beam. This allows the operator to hold the wavelength steady over a shift to better than 0.2%.

The unique feature of the Vanderbilt facility is its excellent facilities available to the medical users. A fully equipped surgical suite is available for surgical studies on animals. This operating theater is equipped with a laser manipulator arm, and a computer-controlled mirror steering system allows the surgeon to make precision cuts in soft or hard tissue using acoustic sensors to monitor the cutting and control incision depth. The user can select the repetition rate of the laser from a local computer and can turn the laser on and off via the computer or a foot switch. There are presently five user rooms in addition to the surgical suite. The beam is delivered in an evacuated beamline to each of the rooms. Remote control of the beamline allows easy switching of the beam from room to room. Several other lasers, including a doubled mode-locked Nd:YAG laser, a tunable dye laser, an argon laser, and an excimer, are available to users.

In the future, the facility plans to install a Smith–Purcell device to provide coherent radiation in the range of 50 to 200 μm. They also have a program to backscatter the infrared laser off the electron beam to provide monochromatic X rays in the 10- to 18-keV range for use in medical imaging. Finally, they have recently obtained funding to add two more floors to their lab in order to provide more space for users and at least one surgical suite qualified for clinical surgery.

6. SUMMARY

I have tried to summarize some of the broad spectrum of science and technology in the field of tunable FELs. This is quite a difficult task. The capabilities of each laser tend to be varied and inconstant due to the constant drive to improve and upgrade the lasers. Although the first FEL operated almost 20 years ago, tunable sources of FELs that could be used by researchers in other fields besides laser physics only became available recently. The pace of development of tunable laser sources has been quite rapid since then. During the same period, FEL was "discovered" in Europe, Japan, China, and the former Soviet Union. Groups in all these countries have built several excellent user facilities and are in the process of bringing more of them on line each year. The present status is that there are six fully functional user facilities with seven more under construction and several more proposed. Federal research support in the United States has remained centered at the existing user facilities but, as the laser designs become smaller and less expensive, some private or state sources are funding efforts to provide users access to this useful research tool.

Although much progress has been made in the understanding and optimization of tunable FELs, much work still must be done in order to optimize the FEL versus cost and performance. I think that the Advanced Free-electron Laser (AFEL) at LANL [57] and the CIRFEL facility being commissioned at Princeton University are the future of low-average-power tunable FELs in the infrared and that this design of laser will allow better optimization of the design for users. For high average power, energy recovery linear accelerators and electrostatic accelerators will provide coverage with continuous electron beams such as those being developed at the University of Central Florida and UCSB or continuously pulsed beams such as in the CEBAF designs [30].

REFERENCES

1. J. M. J. Madey, *J. Appl. Phys.* **42**, 1906–1913 (1971).
2. W. B. Colson, Ph.D. Thesis, Stanford University (1977).
3. R. M. Phillips, *IRE Trans. Electron Dev.* **ED-7**, 231 (1960).
4. R. M. Phillips, *Nucl. Instrum. Meth.* **A272**, 1–9 (1988).
5. A. Doria, G. P. Gallerano, and A. Renieri, *Opt. Commun.* **80**, 417–424 (1991).
6. C. A. Brau, *Free-Electron Lasers*, Academic Press, San Diego (1990).
7. M. L. Stitch and M. S. Bass, Eds., *Laser Handbook*, Vol. 4, North Holland, Amsterdam (1985).
8. S. V. Benson, J. Schultz, B. A. Hooper, R. Crane, and J. M. J. Madey, *Nucl. Instrum. Meth.* **A272**, 22–28 (1988).
9. E. B. Szarmes, S. V. Benson, and J. M. J. Madey, *Nucl. Instrum. Meth.* **A296**, 755–761 (1990).
10. R. H. Pantell *et al.*, *J. Opt. Soc. Am. B* **6**, 1008–1014 (1989).
11. B. A. Hooper, S. V. Benson, R. C. Straight, and J. M. J. Madey, *Nucl. Instrum. Meth.* **A296**, 797–803 (1990).
12. J. N. Eckstein *et al.*, "Additional Experimental Results from the Stanford 3 Micron FEL," in *Free-electron Generators of Coherent Radiation* (G. T. Moore, S. F. Jacobs, H. S. Piloff, M.

Sargent, M. O. Scully, and R. Spitzers, Eds.), Vol. 8, pp. 49–75, Addison-Wesley, Reading, MA (1981).

13. B. E. Newnam *et al.*, *IEEE J. Quant. Elec.* **QE-21**, 867–881 (1985).

14. A. H. Lumpkin *et al.*, *Nucl. Instrum. Meth.* **A296**, 181–185 (1990).

15. L. Elias, *IEEE J. Quantum Electron.* **QE-23**, 1470–1475 (1987).

16. G. Ramian, *Nucl. Instrum. Meth.* **A318**, 225–229 (1992).

17. T. I. Smith, J. C. Frisch, R. Rohatgi, H. A. Schwettman, and R. L. Swent, *Nucl. Instrum. Meth.* **A296**, 33–36 (1990).

18. S. C. Chen, G. Bekefi, S. DiCecca, and R. Temkin, *Nucl. Instrum. Meth.* **A285**, 290–293 (1989).

19. J. C. Goldstein, R. L. Sheffield, B. E. Carlsten, and R. W. Warren, *Nucl. Instrum. Meth.* **A296**, 282–287 (1990).

20. K. P. Paulson, *Nucl. Instrum. Meth.* **A296**, 624–630 (1990).

21. R. W. Warren *et al.*, *Nucl. Instrum. Meth.* **A285**, 1–10 (1989).

22. A. F. G. Van der Meer *et al.*, *Nucl. Instrum. Meth.* **A341**, ABS 23 (1994).

23. M. Curtin *et al.*, *Nucl. Instrum. Meth.* **A296**, 69–74 (1990).

24. M. Billardon *et al.*, *IEEE J. Quantum. Electron.* **QE-21**, 805–823 (1985).

25. G. N. Kulipanov *et al.*, *Nucl. Instrum. Meth.* **A296**, 1–3 (1990).

26. S. V. Benson *et al.*, *Nucl. Instrum. Meth.* **A296**, 110–114 (1990).

27. C. A. Brau, *Nucl. Instrum. Meth.* **A318**, 38–41 (1992).

28. R. Prazeres, J. M. Berset, F. Glotin, D. Jaroszynski, and J. M. Ortega, *Nucl. Instrum. Meth.* **A331**, 15–19 (1993).

29. R. J. Bakker *et al.*, *Nucl. Instrum. Meth.* **A331**, 79–93 (1993).

30. G. Neil, S. V. Benson, "Issues in High Power FEL Design at the Continous Electron Beam Accelerator Facility," in *Laser Resonators and Coherent Optics: Modeling, Technology, and Applications, Proc. SPIE* **1868**, 41–55, SPIE, Bellingham, WA (1993).

31. J. Krishnaswamy *et al.*, "Design and Construction of a Compact Infra Red Free Electron Laser CIRFEL," in *IEEE 1993 Particle Accelerator Conf.*, Vol. 2, pp. 1527–1529, IEEE, Washington D.C. (1993).

32. J. M. J. Madey and R. C. Taber, "Equations of Motion for a Free-electron Laser with a Transverse Gradient," in *Free-electron Generators of Coherent Radiation* (S. F. Jacobs *et al.*, Eds.), Vol. 7, pp. 741–774, Addison-Wesley, Reading, MA (1979).

33. W. B. Colson, *IEEE J. Quantum Electron.* **QE-17**, 1417–1427 (1981).

34. S. V. Benson and J. M. J. Madey, *Phys. Rev.* **A39**, 1579–1581 (1989).

35. R. W. Warren, L. C. Haynes, D. W. Feldman, W. E. Stein, and S. J. Gitomer, *Nucl. Instrum. Meth.* **A296**, 84–88 (1990).

36. R. W. Warren, *Nucl. Instrum. Meth.* **A304**, 512–515 (1993).

37. R. W. Warren, D. W. Feldman, and D. Preston, *Nucl. Instrum. Meth.* **A296**, 558–562 (1990).

38. R. W. Warren *et al.*, *Nucl. Instrum. Meth.* **A331**, 48–51 (1993).

39. P. G. O'Shea *et al.*, *Nucl. Instrum. Meth.* **A331**, 62–68 (1993).

40. A. E. Siegman, *Proc. IEEE* **53**, 277–287 (1965).

41. Y. A. Anan'ev, N. A. Sventsitskaya, and V. E. Sherstobitov, *Sov. Phys. JETP* **28**, 69–74 (1969).

42. R. W. Warren, private communication.

43. G. N. Kulipanov *et al.*, *Nucl. Instrum. Meth.* **A331**, 98–102 (1993).

44. A. E. Siegman, *IEEE J. Quantum Electron.* **QE-28**, 1243 (1992).

45. C. C. Shih, "Analysis of Stable-Unstable Free-Electron Laser Resonators," in *Laser Resonators and Coherent Optics: Modeling, Technology, and Applications, Proc. SPIE* **1868**, 278–285, SPIE, Bellingham, WA (1993).

46. G. T. McNice and V. E. Derr, *IEEE J. Quant. Electron.* **QE-5**, 569–574 (1969).

47. D. E. McCumber, *Bell Syst. Tech. J.* **48**, 1919–1935 (1969).

48. M. Xie and K. J. Kim, *Nucl. Instrum. Meth.* **A318**, 877–884 (1992).

49. R. P. Walker, *Nucl. Instrum. Meth.* **A237**, 366–380 (1985).

50. E. D. Shaw and R. J. Chichester, *Nucl. Instrum. Meth.* **A318**, 47–51 (1992).

51. J. Ortega, private communication.
52. F. Glotin *et al.*, *Nucl. Instrum. Meth.* **A341**, 49–53 (1994).
53. G. A. Barnett, S. V. Benson, and J. M. J. Madey, *IEEE J. Quantum Electron.* **29**, 479–486 (1993).
54. E. B. Szarmes, A. D. Madden, and J. M. J. Madey. Optical phase locking of a 2.856 GHz harmonically modelocked free-electron laser, *J. Opt. Soc. America B.*, in press.
55. T. I. Smith, H. A. Schwettman, K. W. Berryman, and R. L. Swent, "Facilities at the Stanford Picosecond FEL Center," in *Free-electron Laser Spectroscopy in Biology, Medicine and Material Science, Proc. SPIE* **1854**, 23–33, SPIE, Bellingham, WA (1993).
56. C. A. Brau and M. Mendenhall, "The Vanderbilt University Free-electron Laser Center," in *Free-electron Laser Spectroscopy in Biology, Medicine and Material Science, Proc. SPIE* **1854**, 2–10, SPIE, Bellingham, WA (1993).
57. D. C. Nguyen *et al.*, *Nucl. Instrum. Meth.* **A341**, 29–33 (1994).